Engineering 41 (2024) 19–34

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Robotics—Review

Current Status, Challenges, and Prospects for New Types of Aerial Robots

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ARTICLE INFO

Article history:
Received 23 November 2023
Revised 3 May 2024
Accepted 11 May 2024
Available online 31 May 2024

Keywords:
Aerial robot
Morphability
Biomimicry
Perch
Amphibious

ABSTRACT

New types of aerial robots (NTARs) have found extensive applications in the military, civilian contexts, scientific research, disaster management, and various other domains. Compared with traditional aerial robots, NTARs exhibit a broader range of morphological diversity, locomotion capabilities, and enhanced operational capacities. Therefore, this study defines aerial robots with the four characteristics of morphability, biomimicry, multi-modal locomotion, and manipulator attachment as NTARs. Subsequently, this paper discusses the latest research progress in the materials and manufacturing technology, actuation technology, and perception and control technology of NTARs. Thereafter, the research status of NTAR systems is summarized, focusing on the frontier development and application cases of flapping-wing micro-air vehicles, perching aerial robots, amphibious robots, and operational aerial robots. Finally, the main challenges presented by NTARs in terms of energy, materials, and perception are analyzed, and the future development trends of NTARs are summarized in terms of size and endurance, mechatronics, and complex scenarios, providing a reference direction for the follow-up exploration of NTARs.

1. Introduction

The earliest applications of aerial robots were in the military domain, where they were utilized to execute perilous missions in order to reduce pilot risks and enhance operational efficiency. Aerial robotic technology has rapidly evolved since then, and its widespread adoption has expanded to the civilian sector. Aerial robots are currently employed in a variety of civil tasks such as electrical grid inspections, agricultural monitoring, forest fire surveillance, search-and-rescue operations, and geographical surveying [1]. Nevertheless, traditional aerial robots exhibit several shortcomings when confronted with increasingly complex and demanding tasks. These limitations stem from their limited flight configurations and motion patterns, which result in drawbacks such as high noise emissions, large physical dimensions, limited endurance, and inability to navigate complex constrained environments.

Research on new types of aerial robots (NTARs) has emerged as a focal point for academic institutions worldwide. Internationally acclaimed laboratories specializing in aerial robotics have been established at prominent universities, such as Harvard University's Microrobotics Laboratory [2], Imperial College London's Aerial Robotics Lab [3], Hong Kong University of Science and Technology's Aerial Robotics Group [4], and Zhejiang University's Field Autonomous System and Computing Laboratory [5]. Globally, scholars have spearheaded the development of diverse arrays of NTARs, encompassing aerial robots that simulate animal flight, aerial robots capable of perching on natural and engineered surfaces, aerial robots with swimming or crawling capabilities, and aerial robots equipped with manipulator arms. Among the emerging multitude of aerial robot morphologies, we collectively designate aerial robots possessing the characteristics of morphability, biomimicry, multi-modal locomotion, and manipulator attachment as NTARs (Fig. 1).

1.1. Morphability

NTARs with morphing capabilities primarily encompass fixed-wing and rotor-wing aerial robots. Morphing in fixed-wing aerial robots involves airfoil-level morphing and wing-level morphing. Airfoil-level morphing comprises variable camber and variable thickness adaptations, whereas wing-level morphing includes span-wise morphing, variable sweep, twist morphing, and folding wing mechanisms [6]. In contrast, rotor-wing aerial robots undergo morphing through propeller folding, airframe folding, and airframe bending.

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https://doi.org/10.1016/j.eng.2024.05.008

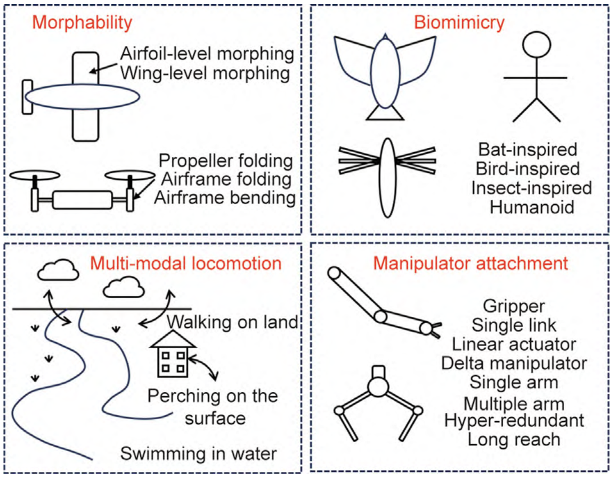

Fig. 1. Definition of NTARs.

1.2. Biomimicry

Biomimetic aerial robots are a promising and forward-looking category of NTARs. These robots are inspired by biological systems in terms of design and functionality. More specifically, biomimetic aerial robots are inspired by the characteristics and behaviors of organisms in the natural world and replicate specific biological features to achieve enhanced performance, efficiency, and adaptability. Current biomimetic aerial robots can be categorized according to their inspiration, such as those inspired by bats [7], birds [8–12], and insects [13], and humanoid aerial robots [14].

1.3. Multi-modal locomotion

By employing multi-modal locomotion, NTARs can switch between different motion modes to enhance their task execution efficiency. For example, they may be submerged in environmental samples during marine surveillance. Long-distance cruising can be made more energy efficient through perching, which extends endurance. During search-and-rescue missions, NTARs can walk or crawl to reach places where flights are not feasible. Multi-modal locomotion enhances the adaptability, efficiency, stability, and maneuverability of NTARs, enabling them to perform a wide range of tasks and operate effectively in diverse environments.

1.4. Manipulator attachment

The inclusion of manipulators enables NTARs to perform operational tasks during flight. This capability holds significant promise for applications such as high-altitude inspection and maintenance, where NTARs can significantly reduce the time, cost, and risks associated with human labor. Currently, NTARs are equipped with a variety of manipulators, including grippers, single arms, linear actuators, delta manipulators, multiple arms, hyper-redundant systems, and long-reach manipulators [15].

In previous studies, scholars have conducted comprehensive reviews on various types of aerial robots, including small autonomous drones [16], morphing wings for aerial robots [6], flapping-wing aerial robots [13], multi-modal robots [17], perching aerial robots [18,19], and operational aerial robots [15,20]. Based on these reviews, this present paper presents a synthesis and summary of the latest research on aerial robots. In contrast to previous reviews that focused primarily on individual types of aerial robots, this study encompasses a wide range of aerial robots and provides a thorough analysis and summary of each type. Consolidating the research on NTARs enables a comprehensive understanding of the commonalities and differences among different types, thereby offering a more comprehensive reference for the future research and development of aerial robots. This paper begins with an introduction to the key technologies underpinning NTARs. Subsequently, we summarize the predominant NTAR systems that are currently in existence. Finally, we delve into the prospective directions and challenges for the future development of NTARs.

2. Key technologies for NTARs

The key technologies for NTARs include materials and manufacturing technology, actuation technology, and perception and control technology. Materials and manufacturing technology affects various aspects of aerial robots, including their weight, strength, endurance, morphing capabilities, and cost, making this technology a pivotal factor in NTAR design. An actuator serves as the power source for aerial robots, providing the necessary thrust or power to enable flight or maintain hovering in the atmosphere. Hence, actuation technology is the core element in NTAR design and directly influences NATRs' performance and capabilities. Perception and control technology is crucial for the navigation, obstacle avoidance, task execution, autonomous decision-making, and stable flight of aerial robots. Sensors are employed to gather environmental information, and control systems utilize data from these sensors to execute a wide array of operations. The combined effects of these three key technologies enable NTARs to operate across diverse domains. Extensive research has been conducted in these three areas, as depicted in Fig. 2 [7,21–29].

2.1. Materials and manufacturing technology

One of the distinguishing features of NTARs is their morphing capability, which primarily involves wing deformation. Consequently, research and advancements in the materials and manufacturing technology for NTARs have predominantly focused on wing-related innovations. The materials employed in NTARs are chosen to contribute to an overall weight reduction, thereby enhancing the robot's maneuverability and efficiency. Given that the geometric shape of the wings is a critical factor that influences the wings' aerodynamic performance, these materials should enable the robot to alter its wing shape during various flight phases or tasks, thereby enhancing its performance and versatility. To achieve this, wing materials must possess increased strength and rigidity to mitigate the weight of the robot. These materials should be designed with flexibility and adaptability to accommodate various flight requirements. Wing materials that fulfill these criteria primarily include flexible membranes, mechanical metamaterials, and shape-memory alloys (SMAs), as listed in Table 1.

2.1.1. Flexible membranes

Flexible membranes are thin, pliable materials that are typically composed of elastic or flexible polymers. These materials possess the key characteristics of bending, stretching, twisting, and similar deformations under the influence of external forces, with the ability to return to their original state. Employing flexible membranes as wing materials for NTARs effectively reduces the weight of the robot, thereby enhancing its flight efficiency. Moreover, flexible membranes facilitate intricate deformations, allowing a realistic emulation of natural flight maneuvers. For example, Bat Bot [7], a flapping-wing aerial robot inspired by bats and designed by the Graduate Aerospace Laboratories of the California Institute of Technology, utilizes highly stretchable silicon-based membrane wings. Similarly, RoboBee [30–34], developed by Harvard University's Microbotics Laboratory, employs polyester film wings.

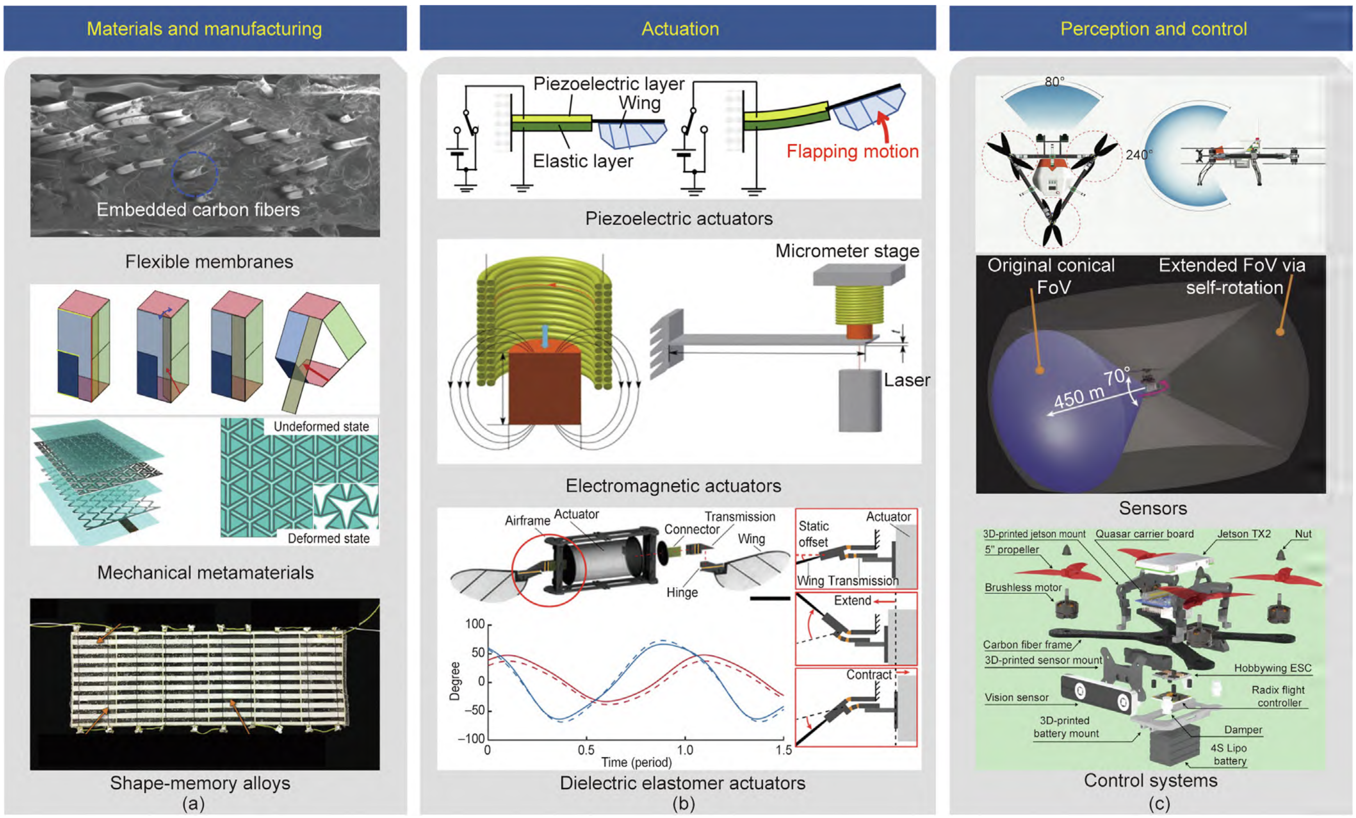

Fig. 2. Key technologies for NTARs. (a) Materials and manufacturing technology include flexible membranes, mechanical metamaterials, and shape-memory alloys, among which mechanical metamaterials are divided into origami and kirigami. (b) Actuation technology is divided into piezoelectric actuators, electromagnetic actuators, and dielectric elastomer actuators. (c) Perception and control technology is divided into the sensors and the control systems. FoV: field of view; ESC: electronic speed controller. (a) Reproduced from Refs. [7,21–23] with permission; (b) reproduced from Refs. [24–26] with permission; (c) reproduced from Refs. [27–29] with permission.

Table 1
Characteristics of the three types of wing materials used in NTARs.

Wing materials	Deformation condition	Deformation capability	Applicable range	Disadvantage
Flexible membranes	External force	Bend, stretch, twist, and fold	Flapping-wing	• Easily damaged • Low performance
Mechanical metamaterials	Load application	Fold, bend, and twist	Fixed-wing and rotor-wing	• Poor reconfigurability • Poor reversibility
SMAs	Thermal and stress	Bend and twist	Fixed-wing	• Continuous energy input

However, flexible membranes are relatively thin and susceptible to mechanical pressures and external environmental factors that may lead to damage. Moreover, they may not satisfy the performance requirements during high-performance flight scenarios. Consequently, the use of flexible membranes in flapping-wing aerial robots is limited.

2.1.2. Mechanical metamaterials

Mechanical metamaterials offer high degrees of flexibility and scalability. By introducing folds (origami) or cuts (kirigami) into a material, predetermined three-dimensional (3D) shapes can be obtained during deformation. Origami is a promising technique that utilizes two-dimensional laser micromachining to engrave intricate folding patterns into multilayer materials, yielding lightweight structures with complex folding behaviors. Origami technology has been applied in fixed-wing aerial robots [35] and rotor-wing aerial robots [21,36–38]. Notably, a novel design known as "solar-powered shape-changing origami microfliers" was proposed by the University of Washington in the United States [39]. This innovative concept involves integrating a circuit directly onto the folded origami structure, including a programmable microcontroller, Bluetooth radio, solar power harvesting circuit, pressure sensor for height estimation, and temperature sensor.

Kirigami is a variant of origami that combines cutting and folding techniques. Systems constructed using kirigami networks benefit from the bending modes generated by delicate structures, which are energetically favorable, making them particularly appealing for morphological changes. For example, deformable aerial robots based on kirigami composite materials [22] designed by Virginia Tech in the United States exhibit remarkable deformability.

However, the reconfigurability and reversibility of deformation systems based on mechanical metamaterials may be constrained, as these structures often exhibit bistability, necessitating the application of loads to maintain their shape or permanent deformation to achieve shape changes.

2.1.3. Shape-memory alloys

SMAs are a category of metal alloys with unique properties, such as the ability to return to their predefined shapes from an altered configuration when subjected to thermal or stress-induced stimuli, in what is known as the shape-memory effect.

For example, a team led by Sung-Hoon Ahn from Seoul National University in the Republic of Korea designed a series of composite materials based on SMAs and applied them to various wing deformations in fixed-wing aerial robots, including twist-morphing wing segments [40], morphing winglets [41], and morphing flaps [23].

Compared with mechanical metamaterials, which impose geometric constraints at the initial design stage, SMAs offer greater flexibility. However, deformation mechanisms based on SMAs require continuous stimulation or energy input to maintain the reconfigured shapes, as these shapes depend on specific conditions or external field interactions. Consequently, when selecting wing-deformation materials, a comprehensive evaluation of the design objectives, application requirements, and material characteristics is essential to determine the most suitable choice. In certain scenarios, SMAs are an appealing option, particularly for applications requiring light weight, compactness, rapid response, and programmable shape changes. SMAs can even be used to drive bionic claws [42,43]. These examples demonstrate SMAs' strong applicability in the field of aerial robots.

2.2. Actuation technology

Actuators serve as the metaphorical beating hearts of aerial robots by providing them with the power and control required to perform various tasks and flight operations; thus, actuators are a critical component of NTARs. Traditional large-scale aerial robots often use direct-current (DC) motors as actuators. However, as the size of aerial robots decreases to that of the level of micro-aerial vehicles, the energy-conversion efficiency of DC motors decreases significantly. This is particularly pronounced in sub-kilogram flapping-wing micro-aerial vehicles (FWMAVs), where it is necessary to balance the mass and volume of the aircraft while ensuring sufficient power for takeoff. Consequently, it is imperative to explore alternative actuators to replace DC motors. Currently, the mainstream actuation strategies for sub-kilogram FWMAVs include piezoelectric actuators, electromagnetic actuators, and dielectric elastomer actuators, as listed in Table 2.

2.2.1. Piezoelectric actuators

Piezoelectric actuators generate mechanical displacements or vibrations via piezoelectric effect. When an external electric field is applied, piezoelectric materials undergo deformation. The flapping motion of FWMAVs aligns effectively with the characteristics of piezoelectric actuators, making the latter the most promising mechanism for sub-kilogram FWMAVs. For example, both RoboBee [30–34] and RoboFly [44–48], designed by researchers at the University of Washington in the United States, utilized piezoelectric actuators.

A research team led by Takashi Ozaki in Japan has been dedicated to the development of sub-kilogram FWMAVs. Their initial design featured a twin-wing FWMAV driven by two monomorphic piezoelectric actuators, which enabled tethered flight [49]. Subsequent iterations involved a hexawing FWMAV with six piezoelectric actuators powering the wings [50]. These vehicles were powered by wireless radio-frequency energy, similar to the X-Wing RoboBee and the four-wing RoboFly, which enabled wireless takeoff. Their latest design incorporated an octawing FWMAV with eight piezoelectric monocrystal chip actuators that drove the wings powered by an onboard battery [24]. This is currently the first tailless FWMAV with an insect-scale weight powered by a battery.

Although piezoelectric actuators can generate the high-speed reciprocating motion required for flapping flight, they require lightweight and efficient boost converters that are capable of producing voltage levels in the order of 200 V. This conversion process typically utilizes energy sources such as solar power [34], lasers [45], radio frequency [50], and batteries [24]. However, these conversion circuits significantly reduce the payload capacity of FWMAVs.

2.2.2. Electromagnetic actuators

The low operating voltage of electromagnetic actuators eliminates the need for complex power electronics equipment, making them a successful driving strategy for sub-kilogram FWMAVs. For example, a team led by Palak Bhushan at the University of California in the United States investigated the application of electromagnetic actuators in micro-aerial vehicles, successfully deploying the actuators in milligram-scale [51] and sub-milligram-scale FWMAVs [52]. Furthermore, they demonstrated takeoff in a spinning micro-aerial vehicle [53]. Similarly, Zou et al. [25] designed an 80 mg FWMAV using a high-frequency electromagnetic actuator as the robot's propulsion system.

Electromagnetic actuation generates the energy required to propel micro-aerial vehicles into the air without the need for a boost circuit. However, this can result in higher energy costs and heat generation.

2.2.3. Dielectric elastomer actuators

Currently, the most advanced sub-kilogram FWMAVs are primarily driven by rigid microscale actuators, including piezoelectric actuators and electromagnetic actuators. Owing to the high lift demands of FWMAVs, which necessitate high power density and bandwidth, the majority of FWMAVs use piezoelectric actuators. However, previous studies [54,55] have indicated that piezoelectric actuators are prone to cracking under pulsed loads or significant strains. The low fracture strength of piezoelectric actuators limits the flight capabilities of robots, making it challenging for piezoelectrically driven FWMAVs to achieve high maneuverability and post-collision survival. Therefore, dielectric elastomer actuators with morphing capabilities can be considered as promising alternatives.

Dielectric elastomer actuators consist of an incompressible elastomeric layer sandwiched between a pair of flexible electrodes. When a potential difference is applied between the two electrodes, the electrostatic forces deform the elastomer, thereby generating a

Table 2
Advantages and disadvantages of the three main types of actuators.

Actuators	Principle	Advantages	Disadvantages
Piezoelectric actuators	Inverse piezoelectric effect	• High lift-to-weight ratio • High operating stresses • High frequencies	• High-efficiency boost converter • Low breaking strength • Low failure strain
Electromagnetic actuators	Electromagnetic effect	• Low operating voltage • No need for boost circuit	• More energy costs • More heat
Dielectric elastomer actuators	Electrostatic pressure	• High power density • High transduction efficiency • Large deformation ability	• High driving voltage

mechanical strain that can be used for propulsion. SoftFly [26,56–58], designed by researchers at Harvard University in the United States, serves as a typical example of an FWMAV employing dielectric elastomer actuators. However, owing to their shortcomings, many dielectric elastomer actuators exhibit dielectric breakdowns and short lifespans when operating under peak performance conditions, or unexpected damage. In a recent study [59], the electrodes of the dielectric elastomer actuators in SoftFly were optimized, enabling them to withstand over 100 punctures while maintaining a high power density for controlled flight.

2.3. Perception and control technology

Perception and control technologies enable robots to sense, comprehend, and respond to their surroundings. In particular, in tasks such as search and rescue, surveillance, and monitoring, these technologies enable NTARs to identify and track targets such as individuals, vehicles, and structures. In obstacle avoidance and navigation, sensor-based perception allows NTARs to continually detect obstacles and terrain changes in real time, thereby preventing collisions and devising optimal flight paths. This ability is of paramount importance to ensure the safe operation of NTARs in intricate and uncertain environments.

The primary role of the control system is to provide control signals that guide the NTAR during its flight. Consequently, the design of the control system is important in the configuration and overall structure of an NTAR. With the correct design in place, NTAR flights become safer, reducing the likelihood of economic losses.

2.3.1. Sensors

Current research in perception technology primarily focuses on imaging techniques that use visual and laser sensors. Visual imaging technology involves capturing images by collecting existing light through camera lenses. However, traditional cameras have severely limited fields of view that significantly constrain the perceptual capabilities of NTARs. Therefore, generating images with a larger field of view is one of the focal points of current research on visual imaging technology for NTARs. Fish-eye cameras [60] and reflective cameras [61], which inherently possess a broader field of view, have been successfully applied in NTARs. Although these cameras can achieve fields of view exceeding 180° and even up to 360°, their images often exhibit noticeable distortions that require appropriate compensation. Therefore, sensor fusion that involves multiple visual sensors is a promising approach, including the use of two fish-eye cameras [62], four fish-eye cameras [27,63], four stereo cameras [64], or five traditional cameras [65].

However, relying solely on images makes it challenging to directly measure the distance to objects, which necessitates the use of other sensors to obtain depth data. In addition, visual sensors are sensitive to lighting conditions, and factors such as strong light, weak light, or backlighting can affect image quality and sensor performance. Laser imaging technology uses light detection and ranging (LiDAR) to generate laser beams that measure the distance to target objects, thus creating 3D point cloud information within the spatial environment. The underlying principle relies on measuring the round-trip time of light through laser emission, propagation, and reception to determine the distance. Consequently, LiDAR remains unaffected by environmental lighting conditions. Researchers have conducted extensive studies on laser imaging technology for aerial robots, including the segmentation of areas of interest from 3D point clouds [66], optimal LiDAR installation orientations [67], and sensor-fusion approaches involving LiDAR, cameras, and inertial measurement units [68].

The cost and weight of traditional 3D LiDAR are significantly higher than those of cameras. To achieve a lightweight design, a novel solution that leverages the autonomous motion of aerial robots to assist in laser imaging has been proposed. Powered-flying ultra-underactuated LiDAR sensing aerial robot, designed by researchers at the University of Hong Kong in China, is an agile self-rotating aerial robot [28]. By autonomously rotating, it extends the laser imaging range to 360°, thereby enhancing its perception capabilities, task efficiency, and flight safety.

2.3.2. Control systems

The utilization of robust algorithms, dedicated hardware, and adept system integration is necessary to enable NTARs to perform more challenging flight maneuvers and exhibit enhanced flight agility. However, most aerial robots developed by research groups are based on fragmented research in both the hardware and software domains. This fragmentation limits the existing aerial robots to task-specific capabilities, rendering them unsuitable for diverse mission requirements. To achieve multi-tasking capabilities and high-performance flight, the control systems of aerial robots must possess sufficient computational power to simultaneously run the onboard estimation, planning, and control algorithms. With the advent of learning-based approaches, efficient hardware acceleration is required for neural network inference. Thus, the development of highly integrated, specialized control systems for aerial robots not only maximizes computational resources but also effectively reduces the size and weight of aerial robots, thereby enhancing flight performance.

Numerous open-source aerial robotics research platforms have been introduced to date, such as the Fast Lightweight Autonomy platform [69], Multi-robot Systems Group UAV System quadrotor [70], Autonomous Systems Lab-Flight [71], Massachusetts Institute of Technology-Quad [72], and General Robotics, Automation, Sensing and Perception-Quad [73]. All these platforms are optimized for relatively heavy sensor configurations or agile flights in non-autonomous environments, making it challenging to simultaneously address the propulsion capabilities required for autonomous agility and the computational resources necessary for genuine autonomy. Researchers at the University of Zurich in Switzerland have introduced Agilicious [29], a hardware and software framework tailored for autonomous, agile quadrotor flight. Its control system is equipped with graphics processing unit acceleration hardware for real-time perception and neural network inference, thus enabling complex neural network architectures to operate at high frequencies while simultaneously executing latency-sensitive optimization-based control algorithms onboard the drone. Furthermore, it supports both model-based and neural-network-based controllers.

3. NTAR systems

At present, NTAR systems are extensively used in various domains. This paper, according to its definition of NTARs, provides an overview of some of the prominent NTAR systems, including FWMAVs, perching aerial robots, amphibious robots, and aerial manipulation robots. FWMAVs are typical biomimetic aerial robots that can achieve highly maneuverable flights by simulating the flight patterns of flying creatures in the natural world. Perching aerial robots and amphibious robots possess multi-modal locomotion capabilities that enable them to perch on surfaces or move across various media. Operational aerial robots that are equipped with manipulators can perform a wide range of tasks. The deformability of NTARs is effectively employed in these four categories of NTAR systems.

3.1. Flapping-wing micro-aerial vehicles

With the advancement of NTAR technology, the research focus has shifted from high-speed flight to reduced size. In the

development of micro-aerial vehicles, engineers have turned to nature for inspiration, drawing from excellent examples of small creatures in the natural world to design new flight structures such as FWMAVs. Flying creatures in the animal kingdom can be broadly categorized into three groups: birds, bats, and insects. Previously, flight structures based on birds and bats have been successfully replicated [7–11]. However, the complex mechanical structures of these creatures pose challenges when downsizing the NTAR. Because of the highly flexible nature of insect-scale FWMAVs, these systems have a high number of degrees of freedom. Controlling flexible structures requires the consideration of vibrations and deformations, which increases the complexity of the control algorithms. In addition, aerodynamic effects introduce significant uncertainties into the control of insect-scale FWMAVs, including airflow disturbances and vortices [13]. These uncertainties make it challenging to accurately model and predict the response of the system, further complicating control efforts.

Successful examples of insect-scale FWMAVs include the DelFly series [74–76], RoboBee series[30–34], RoboFly series [44–48], and SoftFly series [26,56–58], as depicted in Fig. 3 [26,30–34,44–48, 58,74–76]. The DelFly series primarily focuses on the flight performance of insect-scale FWMAVs with aircraft weights in the gram range. The RoboBee and RoboFly series aim to reduce the mass and size of insect-scale FWMAVs, aspiring to achieve autonomous flight with sub-gram weights. The SoftFly series primarily focuses on the field of soft robotics, accomplishing the flight of sub-gram soft-actuated robots.

3.1.1. DelFly

The DelFly series, developed by a research team at the Delft University of Technology in the Netherlands, was designed to mimic the flight and agility of insects, as illustrated in Fig. 3(a). In 2005, the team designed DelFly I, weighing 21 g [74]; it was capable of both fast and slow flights. DelFly II, designed in 2007, was smaller in size, weighing 16 g [74] and was capable of hovering. In 2008, the team further reduced the size of DelFly by introducing the all-new DelFly Micro, weighing 3 g [74]. DelFly Explorer, designed in 2013 and weighing 20 g, was the first FWMAV capable of autonomous flight [75]; it could autonomously take off, control its altitude, and be applied to sparse obstacle-avoidance tasks. DelFly Nimble, developed in 2018, is a tailless FWMAV weighing 29 g [76]; it can hover and fly in any direction and is controlled by two pairs of flapping wings.

3.1.2. RoboBee

RoboBee, developed by researchers at the Wyss Institute for Biologically Inspired Engineering at Harvard University in the United States, aims to emulate the flight capabilities and behaviors of insects such as bees, as depicted in Fig. 3(b). The first-generation RoboBee [30], designed in 2008, weighed 60 mg and could generate sufficient thrust for vertical acceleration using external power. The second-generation RoboBee [31], created in 2013, weighed 80 mg and achieved stable untethered hovering and basic controlled flight maneuvers. The third-generation RoboBee [32], introduced in 2016 with electrode attachments, weighed 84 mg and repeatedly transitioned between flying and perching by using its top-mounted electrodes. In 2017, a hybrid aerial–aquatic insect-scale FWMAV was redesigned; it weighed 175 mg [33] and was capable of aerial hovering, aerial-to-water transitions, swimming, and water-surface takeoff and landing. In 2019, the newly designed X-Wing RoboBee [34], which featured a four-flapping-wing structure and weighed 90 mg, was capable of continuous untethered flight, enabled by solar panels mounted on top.

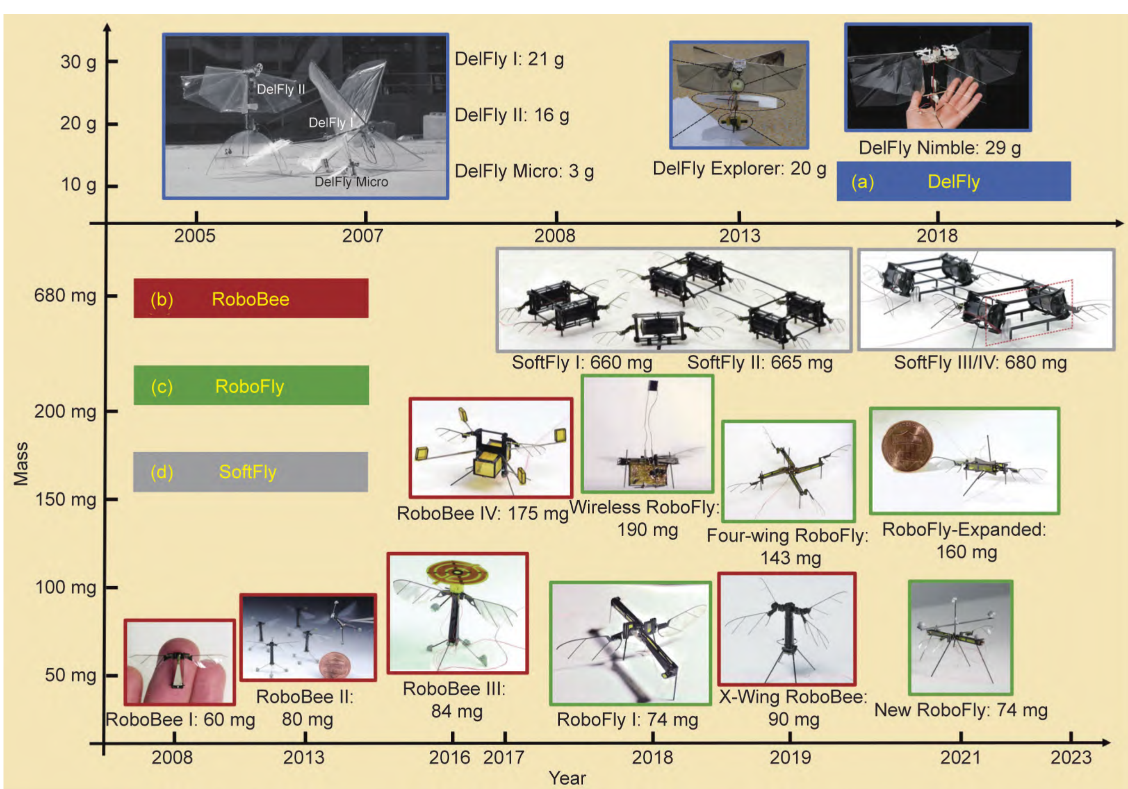

Fig. 3. Current successful cases of insect-level FWMAV research. (a) DelFly; (b) RoboBee; (c) RoboFly; (d) SoftFly. (a) Reproduced from Refs. [74–76] with permission; (b) reproduced from Refs. [30–34] with permission; (c) reproduced from Refs. [44–48] with permission; (d) reproduced from Refs [26,58] with permission.

3.1.3. RoboFly

RoboFly is an insect-scale FWMAV that was developed by a research team at the University of Washington in the United States to achieve autonomous flight and stable mid-air hovering, as illustrated in Fig. 3(c). The initial design of RoboFly was motivated with the aim of simplifying the RoboBee manufacturing process. The first-generation RoboFly, developed in 2018, weighed 74 mg [44]. In the same year, a 190 mg RoboFly was created to achieve the first instance of wireless takeoff for an insect-scale FWMAV [45]. The four-winged RoboFly, designed in 2019 and weighing 143 mg, enabled mid-flight turning maneuvers and hovering position control through motion-capture feedback [46]. To further enhance RoboFly's flight performance, the 160 mg RoboFly-Expanded was introduced in 2021 [47]. This version demonstrated the yaw control of a passively hinged flyer to achieve controlled flight. Building on RoboFly-Expanded, a new RoboFly weighing only 74 mg was developed in the same year [48]. It also exhibited controlled hovering flight and closed-loop landing, building upon the earlier results.

3.1.4. SoftFly

SoftFly is a soft-actuated FWMAV developed by a research team led by Yufeng Chen at Harvard University in the United States, as depicted in Fig. 3(d). The initial design, SoftFly I [26], was developed in 2019 and had a total weight of 660 mg. In 2021, the subsequent iteration, SoftFly II [56], had a slightly increased weight of 665 mg but introduced the capability for the robot to achieve collision recovery during the flight and complete a somersault in 0.16 s. To extend the robot's endurance, SoftFly III [57] was designed in 2022 with a weight of 680 mg and the capability of a sustained hovering flight for up to 20 s. Furthermore, in 2023, SoftFly IV [58] introduced a novel three-layer wing-hinge design for effective heading control during hovering flights. It also exhibited an extended hover time of 40 s—the longest hover time among the existing sub-gram FWMAVs.

In summary, there has been a significant improvement in the research outcomes of FWMAVs compared with earlier studies. Progress has been made in weight, endurance, and flight performance. These advancements offer substantial advantages for NTARs in executing monitoring and reconnaissance missions. However, because of the small size of FWMAVs, their payload capacity is limited. Consequently, they cannot carry large batteries or bulky sensors, which restricts them to laboratory research and makes it challenging for them to effectively perform monitoring and reconnaissance tasks in practical applications.

3.2. Perching aerial robots

Because of battery capacity limitations, NTARs cannot sustain missions for extended periods. In contrast to NTARs, flying animals such as birds, bats, and insects can land and take off on various complex natural and engineered surfaces. They can regain energy for prolonged flights by perching, which enables them to cover longer distances compared to aerial robots. For the aerial robots that are incapable of obtaining energy during flight, perching is currently a research focus for conserving or replenishing power.

The research challenges in perching aerial robots primarily involve three aspects: approach, perch, and departure. During the approach phase, advanced perception systems are required to identify the target area and surrounding environment. Precise navigation algorithms are essential to ensure that NTARs avoid collisions and maintain a predetermined trajectory during the process. Maintaining a perch at the target position requires sophisticated stability-control algorithms to counter potential wind, airflow, and other external disturbances. Departing from the target position also requires a safe and reliable control system to ensure that the robot leaves without damage and can effectively navigate around obstacles [18]. Currently, aerial robots primarily employ three perching mechanisms: spines, adhesives, and grippers, as illustrated in Fig. 4 [31,77–84].

3.2.1. Spines

NTARs can utilize end-effectors equipped with spines to achieve perching by penetrating the target or attaching to rough target surfaces using microspines that resemble barbs. The drawback of penetrative perching [77,85] lies in the requirement for additional circuitry to enable the penetration and release of spines. This significantly increases the weight of the aerial robot, leading to reduced endurance and payload capacity.

The use of microspines for adhesive perching eliminates the need for additional power and allows attachment and detachment with minimal energy consumption. However, for fixed-wing aerial robots, attachment perching involves the performance of a pitch maneuver immediately before reaching the perching surface, followed by a ballistic phase influenced by aerodynamic forces. Consequently, in earlier research by Desbiens' team [78,86,87], a solution was proposed to enable fixed-wing aerial robots to complete the perching and takeoff processes. However, the suspension touchdown envelope was of negligible size. In 2017, Desbiens' team at the University of Sherbrooke in Canada further developed Sherbrooke's multi-modal autonomous drone (S-MAD) [88], the first fixed-wing aerial robot capable of assisted perching and takeoff through thrust. In the same year, a biomimetic and dexterous manipulation laboratory led by Mark Cutkosky at Stanford University in the United States demonstrated the Stanford Climbing and Aerial Maneuvering Platform [89], a quadrotor aerial robot capable of passive outdoor surface perching, climbing, and taking off. It also employs microspine adhesion for attaching to rough surfaces.

In summary, although the use of microspines enables aerial robots to perch, it limits the perching surface to soft targets or rough walls. Thus, there are limitations associated with both the spine penetration and adhesion methods.

3.2.2. Adhesives

Adhesion is a commonly used mechanism for achieving perching in NTARs owing to its adaptability to various perching surfaces, including smooth ones. Methods employing chemical adhesives include the use of adhesive materials [90], directional dry adhesives in spring-lever systems [91,92], articulated nondirectional dry adhesives [79], and directional dry adhesive grippers [93]. Notably, FlyCroTug [94], designed at Stanford University in the United States, incorporates both adhesive and microspine mechanisms to achieve perching.

Although chemical adhesives can achieve perching through a simple attachment mechanism, they tend to be either irreversible or difficult to detach. The use of suction cups eliminates these drawbacks. For example, suction can be generated using a vacuum pump installed on the robot [80]. Alternatively, a redundant, fluidic-statically enhanced, bio-inspired disk can achieve adhesion similar to that of a biological disk [81].

These adhesive devices are not suitable for sub-gram FWMAVs. Therefore, researchers have focused on the use of electrostatic adhesives for perching. One of the most successful applications of electrostatic adhesives to NTARs is the third-generation RoboBee [31]; its designed electrostatic adhesives generate attractive forces between the accumulated charges on the patch and substrate, enabling RoboBee to perch and detach from nearly any material, including glass, wood, and natural leaves.

For larger-mass FWMAVs, the adhesion capability of electrostatic adhesives may be insufficient. As a solution, Li et al. [82] designed an aerial wall-amphibious robot with a hybrid flapping/rotor-wing propulsion layout. Flapping wings were employed for

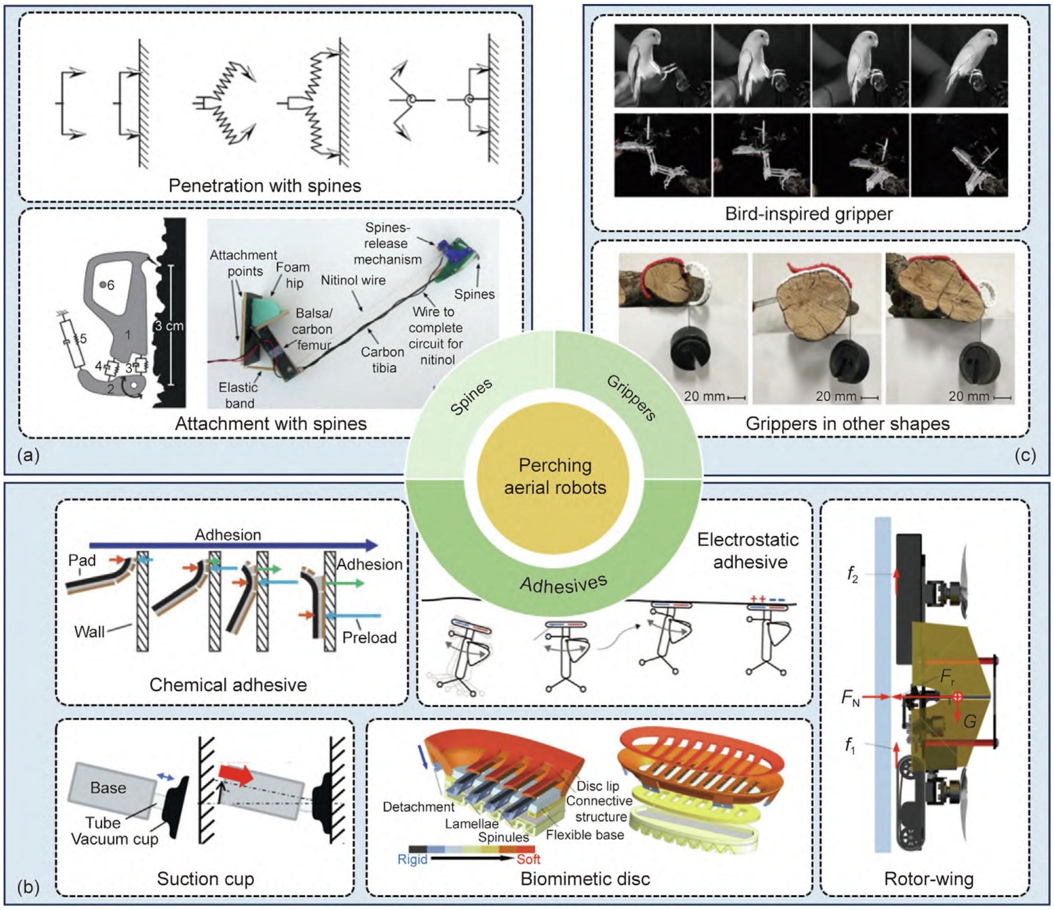

Fig. 4. Perching aerial robots. (a) Methods of using spines for perching include penetration and attachment; (b) methods of using adhesives for perching are divided into chemical adhesive, suction cups, biomimetic discs, electrostatic adhesive, and rotor-wings; (c) methods of using grippers for perching include bird-inspired grippers and grippers in other shapes. f_1 and f_2: the friction on the belts and battery, respectively; F_N: the total support force of the wall on the robot; F_r: the total negative pressure from the rotors; G: the gravitational force of the Earth. (a) Reproduced from Refs. [77,78] with permission; (b) reproduced from Refs. [31,79–82] with permission; (c) reproduced from Refs. [83,84] with permission.

flight, whereas rotor wings were used to generate negative pressure for wall adhesion.

In summary, adhesive mechanisms offer versatile capabilities for adhering to a wide range of materials. However, chemical adhesion [79,90–93] presents limitations for the transition between perching and takeoff, traditional suction-based systems [80] are sensitive to leakages and external disturbances, and adhesion methods based on fluid statics [81] and electrostatic adhesion [31] do not accommodate perching for larger-mass NTARs. Moreover, adhesive approaches with hybrid propulsion layouts [82] consume a substantial amount of power, which significantly affects the endurance of NTARs.

3.2.3. Grippers

Adhesive perching methods are typically constrained to horizontal or vertical surfaces, making it challenging for NTARs to perch on irregular surfaces. In contrast, birds can effortlessly land in various locations, thanks to the passive adaptation of their feet to the surfaces on which they attempt to perch. In 2011, Doyle et al. [95] first proposed graspers inspired by bird feet; they then designed an initial prototype of a compliant leg mechanism in subsequent work [96]. In 2021, Roderick et al. [83] from Stanford University in the United States introduced a stereotyped nature-inspired aerial grasper (SNAG), one of the most successful bird-inspired graspers to date. Bird-inspired graspers allow fixed-wing aerial robots to perch [97].

When discussing the emulation of bird-like perching, it is essential to mention the flapping-wing aerial robots designed to simulate avian flight. Although insect-sized FWMAVs can easily achieve perching capabilities [31,82], this task is far from straightforward for larger flapping-wing aerial robots. Researchers have conducted extensive fundamental research and applications in this regard [42,98]. Ultimately, in 2022, a team from the Robotics, Vision and Control Laboratory robotics and computer vision group at the University of Seville in Spain achieved the pioneering autonomous perching flight of large flapping-wing aerial robots on tree branches [99]. This achievement faithfully replicates bird-like behaviors, paving the way for the application of flapping-wing aerial robots in remote missions, bird observation, manipulation, and outdoor flight.

In addition to grippers that mimic avian talon shapes, various gripper designs with different configurations have been proposed [38,84,100,101]. A team led by Mirko Kovac from the Aerial Robotics Laboratory at Imperial College London in United Kingdom proposed an innovative adaptive perching mechanism [84]. With microspines placed at the bottom of the grasping module, the aerial robot would be able to autonomously tighten its grip and attach to branches of various diameters and shapes. In their most recent study [38], the team cleverly implemented deformable designs into the perching mechanism of NTARs. This enables the intelligent transformation and adjustment of the body of the robot to perch on structures of different sizes and shapes. Similarly, Ruiz et al. [101] designed a lightweight, flexible aerial robot. This

design, which utilizes deformable arms, enables the robot to perch on irregular surfaces, such as pipes. In contrast to designs that rely solely on dedicated grippers [84,95–100], the ability to perch through self-deformation [38,101] offers a more suitable solution for future aerial robot operations.

In summary, the gripping mechanism for perching is currently the most promising method. This approach can be employed for rotor-wing, fixed-wing, and flapping-wing aerial robots. However, this method restricts possible perching surfaces to cylindrical objects. Nevertheless, in outdoor or wilderness environments, grippers can adapt to the majority of perching scenarios.

3.3. Amphibious robots

With the advancement and proliferation of aerial robots, single-mode aerial robots are gradually becoming inadequate for meeting human needs. Therefore, the development of amphibious robots capable of operating in different media—such as the air, water surfaces, and the ground—has become the focal point of research. Amphibious robots can perform various tasks in diverse environments, demonstrating significant flexibility and adaptability. For example, aerial–aquatic amphibious robots are capable of both swimming in water and flying in air, and aerial–terrestrial amphibious robots can walk on land and fly in air.

Amphibious robots require effective propulsion systems for different media to ensure sufficient thrust and maneuverability in diverse environments. This involves various types of thrusters or transmission systems. In addition, these robots require appropriate attitude-control algorithms and stability-control systems to overcome the instability introduced during medium transitions and thus ensure smooth transitions and prevent unexpected incidents. Research and development in this area have been conducted on various flight platforms, including rotor-wing robots, fixed-wing robots, and biomimetic robots, as illustrated in Fig. 5 [14,102–106].

3.3.1. Aerial–aquatic amphibious robots

Aerial–aquatic amphibious robots have wide-ranging applications in the military, research, environmental, and other fields. They can perform tasks such as amphibious reconnaissance, marine life surveys, underwater structural inspections, and iceberg exploration. To achieve mobility in both water and air, aerial–aquatic amphibious robots must overcome certain challenges: ① Because the difference in density between water and air is three orders of magnitude, it is necessary to generate sufficient power for the robot to move underwater; and ② the transition from water to air requires substantial power to overcome the water resistance. Various aerial–aquatic amphibious robots have been developed, including rotor-wing, fixed-wing, hybrid fixed-rotor, and flapping-wing aerial robots.

Innovative designs have been introduced to allow rotor-wing aerial robots to overcome water resistance and achieve rapid aerial–aquatic transitions. For example, the Naviator series of robots from the New Jersey Institute of Technology in the United States incorporates a dual-level propeller design [107,108], which ensures that a set of propellers is always active either underwater or in air, providing sufficient thrust for transitions. The Loon Copter [102] from the University of Oakland in the United States and the mini unmanned aerial–underwater vehicle [109] from the University of California in the United States employ buoyancy devices to enable seamless transitions between water and air. The aerial–aquatic hitchhiking robot [81] utilizes passive deformable rotors that can expand in air and fold underwater, minimizing the time required for aerial–aquatic transitions and facilitating rapid takeoff.

The wing design of fixed-wing aerial robots can overcome water resistance more effectively than that of rotor-wing aerial robots, giving it higher efficiency and endurance. This design has been validated and applied in various aircraft, including propeller-driven straight-wing aerial robots [110,111] and flying-wing aerial robots [112,113]. Notably, NEZHA [103], developed by Shanghai Jiao Tong University in China, combines multiple rotors with a straight-wing design, enabling extended flight endurance, increased cruising speed, improved hovering capability, and underwater endurance.

Impulsive aquatic escape maneuvers, such as impulsive motion, can be employed to facilitate the rapid emergence of an aerial–aquatic amphibious robot from the water surface. An illustrative example is the AquaMAV [114–116], a variable-sweep wing aerial robot developed by researchers at Imperial College London in United Kingdom. It generates a potent water jet thrust using compressed air to swiftly exit the water and attain the necessary airborne velocity. The same team devised a flying-wing aerial robot powered by solid reactants that swiftly achieves flight velocity by reacting environmental water with carbide powder to produce combustible acetylene gas [104]. Furthermore, FWMAV and RoboBee [32] use hydrogen combustion for impulsive takeoffs from the surface of water.

3.3.2. Aerial–terrestrial amphibious robots

Aerial–terrestrial amphibious robots are capable of executing tasks such as search and rescue, exploration of unknown environ-

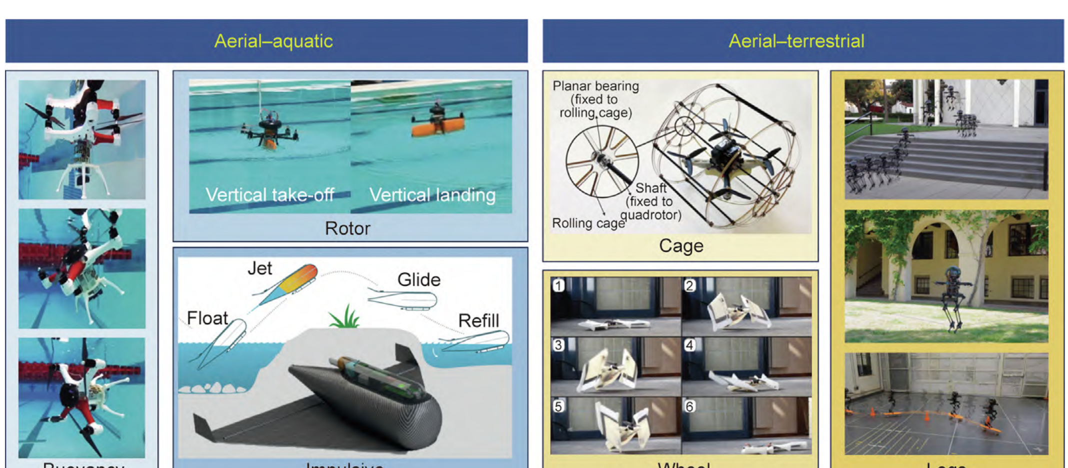

Fig. 5. Amphibious aerial robots on three platforms: rotor-wing, fixed-wing, and biomimetic. Aerial–aquatic amphibious robots achieve transition through buoyancy, rotor, or impulsive methods; aerial–terrestrial amphibious robots achieve transition through cage, wheel, and legs methods. Reproduced from Refs. [14,102–106] with permission.

ments, and environmental monitoring. They offer significant advantages, especially in unstructured terrains such as disaster zones or battlefields, owing to their ability to move both in the air and on the ground. Fixed-wing configurations were frequently employed in the early designs of aerial–terrestrial amphibious robots. Examples include the micro air–land vehicle [117,118] and morphing micro air–land vehicle [119] series from Case Western Reserve University in the United States and the deployable air–land exploration robot [105,120] series from the Swiss Federal Institute of Technology in Lausanne. These aerial–terrestrial amphibious robots used wheel-legs and wheel-wings for terrestrial locomotion. Fixed-wing aerial–terrestrial amphibious robots require sufficient acceleration to transition from ground-based movement to flight, which limits their takeoff options to rooftops or catapult launch systems.

Because of their capability for vertical takeoff, rotor-wing aerial–terrestrial amphibious robots can effectively overcome the challenges associated with transitioning from ground to air. Most rotor-based aerial–terrestrial amphibious robots maneuver on the ground by rolling. For example, in early designs, researchers placed robots inside spherical [121] or cylindrical cages [106] and allowed the cage to roll freely relative to the robot. To simplify the mechanical structure, Kossett et al. [122–124] designed a two-wheeled coaxial-rotor aerial–terrestrial robot. In ground mode, the rotors fold, and the robot uses wheels at both ends of its body for movement. This robot was subsequently upgraded to a quadrotor aerial robot; however, its ground movement mode remained unchanged [125]. Wang et al. [126] developed a four-wheeled multi-rotor aerial robot that combines wheels with rotors. These wheels are shared for both aerial and terrestrial movements, further reducing the weight and design complexity of the robots.

Inspired by nature, bipedal locomotion has emerged as a novel approach for the terrestrial movement of aerial–terrestrial amphibious robots. Examples include bipedal multi-rotor robots [127] and bipedal [128], quadrupedal [48,129], and hexapod [130] FWMAVs. A team from the University of Illinois in the United States designed a multi-modal locomotion robot [131,132], drawing inspiration from flying squirrels. On the ground, it excels in terrestrial locomotion by using four highly articulated legs. In the air, it glides by generating lift between its two legs. Notably, LEONARDO, a biologically inspired bipedal robot with four rotors, was developed by the California Institute of Technology in the United States [14]. Through the synchronized control of its rotors and leg joints, it achieves remarkable agility, allowing it to walk on a tightrope and skateboard.

3.4. Operational aerial robots

Continuous improvements in advanced sensors, communication systems, and autonomous flight technologies have enabled aerial robots to perform a wide range of tasks in various environments. The earliest applications of aerial robots were in the military sector, where they were used for tasks such as reconnaissance, intelligence gathering, and target engagement. These military applications provided valuable experience and technological advancements in the field of aerial robotics. Subsequently, the commercial and industrial sectors recognized the potential of aerial robots to improve efficiency and reduce costs, leading to broader applications of aerial robots. Aerial robots are now widely used to replace human labor in fields such as surveying, manufacturing, and transportation.

During the execution of operational tasks, aerial robots require advanced control algorithms to maintain stability in response to payload changes. High-precision positioning systems and advanced target-alignment algorithms are essential for contact-based operations. Such processes involve complex attitude control and path planning. Formulating effective redundant control strategies is necessary to ensure that aerial robots can operate safely even in the event of component failures [15]. The control precision and payload capacity of the operational aerial robots in various domains are depicted in Fig. 6 [43,133–138].

3.4.1. Survey applications

Aerial robots have extensive applications in the field of surveying, including tasks such as terrain mapping, mineral exploration, agricultural monitoring, and environmental assessment. They can even replace humans in performing highly hazardous inspection tasks, such as power line inspections and wind turbine blade inspections, to name just a few. However, these applications primarily involve the use of sensors. In recent years, NTARs have been demonstrated to be effective for executing manipulation tasks [20]. Aerial manipulation involves the interaction of manipulators with physical objects, including maintaining contact with rigid structures and grasping and transporting objects. Contact-based inspection [139] is one of the most demanding tasks in surveying, with applications in the nondestructive testing of concrete infrastructure [133] and bridge inspections [134]. In particular, the eDrone [135], designed by the Environmental Robotics Laboratory of the Department of Environmental Systems Science at the Swiss Federal Institute of Technology in Switzerland, combines force-sensing cages and tactile-based control strategies to establish and maintain contact with surfaces on branches, enabling the collection of environmental deoxyribonucleic acid and offering a solution for large-scale biodiversity monitoring.

3.4.2. Manufacturing applications

Significant advancements have been made in 3D printing and additive manufacturing in recent years, and they have become mature manufacturing methods. Currently, large-scale additive manufacturing for onsite construction primarily utilizes ground-based robots and gantry systems. However, these technologies require the robot hardware to be scaled up to sizes larger than those of the intended manufactured structures, making the construction sites challenging and hazardous. Therefore, researchers have investigated the possibility of using NTARs for additive manufacturing. The Aerial Robotics Lab at Imperial College London in United Kingdom pioneered the integration of additive layer manufacturing technology with aerial robot technology, developing an aerial 3D printer capable of depositing polyurethane foam to create structures during flight [136]. They proposed a multi-autonomous robot aerial additive manufacturing approach in their recent research [137], enhancing the potential for large-scale applications of aerial robots in the manufacturing domain.

3.4.3. Transport applications

The application of NTARs in logistics and transportation is rapidly expanding. In several Chinese cities, companies have started developing instant food-delivery services using multi-rotor aerial robots [140,141]. Conventional aerial robots primarily use suspension systems or fixed fixtures to carry cargo. Recently, researchers have explored novel cargo-transportation methods for more robust operations; these methods include manipulator [43,142,143] and morphing mechanisms [138].

Attaching a manipulator to a multi-rotor aerial robot makes it easier for the robot to grasp objects [43,142]. When a multi-rotor aerial robot identifies a target for grasping, it hovers, approaches the target, and then grasps it. By contrast, fixed-wing aerial robots must employ a diving strategy inspired by raptors to grasp objects [143]. The High-Performance Robotics Laboratory at the University of California in the United States, designed a deformable quadcopter aerial robot [138]. Instead of executing aerial operations with additional complex mechanisms, this quadcopter aerial robot

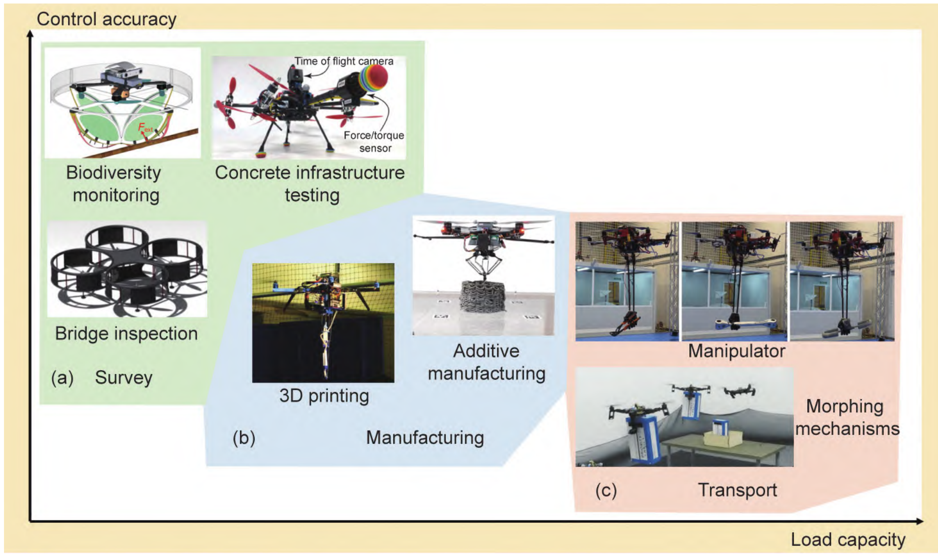

Fig. 6. Application of operational aerial robots. (a) Applications in the survey field include biodiversity monitoring, concrete infrastructure testing, and bridge inspection; (b) applications in the manufacturing field include 3D printing and additive manufacturing; (c) applications in the field of transportation include manipulator and morphing mechanisms. (a) Reproduced from Refs. [133–135] with permission; (b) reproduced from Refs. [136,137] with permission; (c) reproduced from Refs. [43,138] with permission.

allows the vehicle to change shape, perch, and perform simple aerial operations during flight.

However, thus far, an NTAR cannot exert an aerodynamic thrust that exceeds twice its mass. Inspired by the multi-modal motion strategy found in wasps, researchers at Stanford Universityin the United States designed FlyCroTug [94], which firmly adheres to the ground using controllable adhesive forces or microspines and then uses a winch to pull heavy objects. This permits the robot to exert a significant force on tow objects of up to 40 times its mass.

4. Challenges and future prospects

This study provides a comprehensive review of three critical technologies that could be used for NTARs and four major NTAR systems. In this section, we discuss the challenges encountered during the development of NTARs and explore the future trends in this field.

4.1. Challenges for NTARs

NTARs have found widespread applications in various domains, such as surveillance patrols, emergency rescue operations, logistics delivery, and agriculture [16]. In the domain of surveillance patrols, NTARs can provide real-time imagery and data, thereby strengthening the security monitoring of borders, cities, and infrastructure. Emergency rescue operations can swiftly respond to disaster events, conduct search missions, and deliver relief supplies, significantly enhancing rescue efficiency. Moreover, the application of NTARs in logistics delivery enables swifter and more efficient transportation of goods. In agriculture, NTARs can monitor field conditions and effectively improve the agricultural production efficiency.

However, in the process of realizing these applications, NTARs present a series of prominent challenges, with the most significant ones involving energy [144], materials [145], and perception [146]. The quest for more efficient energy storage and conversion technologies is imperative to sustain prolonged flight durations. In the realm of materials, NTARs require lightweight yet sufficiently strong materials to ensure stability during the flight while minimizing weight. Advanced sensory systems are essential for precise navigation and task execution under diverse environments and weather conditions. Addressing these challenges is crucial for the widespread application of NTARs. Therefore, further innovations and breakthroughs are required in the fields of energy-storage and conversion technologies, advanced lightweight material development, and efficient perception systems for NTARs. Table 3 provides a comprehensive analysis summarizing the impacts, existing solutions, difficulties, and breakthrough directions of the three major challenges.

4.1.1. Energy

Larger NTARs can carry large-capacity batteries or internal combustion engines. However, as the size of NTARs continues to decrease, and their payload capacity is reduced, traditional power solutions are no longer adequate for meeting the needs of smaller NTARs. Currently, solutions such as solar power [34], lasers [45], and radio frequency [50] have been proposed but still fall short of providing an extended and stable energy supply to NTARs. Therefore, exploring new energy-supply solutions for NTARs poses a challenge.

4.1.2. Materials

The materials used in NTARs are of paramount importance in terms of the flight performance, structural strength, morphing capabilities, and overall weight. In particular, for FWMAVs, the choice of materials for the body and wings significantly affects the lift-to-drag ratio and endurance. In the case of morphing NTARs, the selection of morphing materials determines the extent, duration, and lifespan of the morphing capabilities. Therefore, the development of novel materials is currently focused on achieving qualities such as light weight, high strength, and enhanced morphing capabilities.

4.1.3. Perception

Perceptual capabilities are the foundation of NTARs' transition from the laboratory to practical operational tasks. However, a

Table 3
Three major challenges presented by NTARs.

Challenge	Impact	Existing solutions	Difficulties	Breakthrough directions
Energy	• Endurance • Load capacity	• Solar energy • Lasers • Radio frequency • Wire	• Long-term energy supply • Stable energy supply	• Wireless power supply • High conversion efficiency
Materials	• Flight performance • Strength and weight • Deformation ability	• Flexible membranes • Mechanical metamaterials • SMA • Carbon fibers • Glass fibers	• Large degree of deformation • Long-term deformation • Repeated deformation	• Light weight • High strength • Strong deformation ability
Perception	• Operational efficiency • Endurance • Flight performance	• Fish-eye camera • Reflex camera • Stereo camera • Traditional camera • Rotating radar	• Small volume • Low quality • High accuracy	• Sensor fusion • Multi-source sensors

significant hindrance to the market deployment of many NTARs is their inability to incorporate environmental perception sensors, which impedes their performance in tasks such as reconnaissance, mapping, and monitoring. This limitation is particularly notable in the case of most FWMAVs, which are often limited to takeoff and landing functions. The precision of the sensors significantly influences the operational efficiency of NTARs. It is worth noting that sensor precision typically scales with the sensor's size and weight, which makes it difficult to achieve both sensor precision and adequate NTAR endurance and flight performance. Therefore, one of the current focal points in the field of NTARs is to address the challenge of achieving high-precision environmental perception using small and lightweight sensors.

4.2. Future prospects for NTARs

In the future, NTARs will lead to profound societal transformations, particularly in areas such as warfare, transportation, and construction. In the context of future battlefields, NTARs have the potential to reshape the landscape of warfare, as they can execute highly complex reconnaissance tasks and aid military forces in formulating effective strategies. Furthermore, NTARs can serve as attack platforms by carrying out strikes behind enemy lines and reducing casualties. In the field of transportation, NTARs will emerge as revolutionary modes of transport. They can collaborate with ground vehicles to provide precise road condition information for surface transportation. Through networked communication between multiple robots, rapid and efficient navigation services can be offered for urban traffic. The application of NTARs in the construction sector is expected to become a key trend in the future, as they can be employed in tasks such as high-altitude construction and maintenance. Moreover, these robots can handle hazardous tasks on construction sites, thereby minimizing the risks to human workers.

NTARs are poised to profoundly alter our lives and the manner in which society operates. Underlying these applications, the developmental trends for NTARs include smaller sizes with extended endurance, electromechanical integration, and operational capabilities in increasingly complex scenarios, as depicted in Fig.7.

4.2.1. Size and endurance

The size and endurance of NTARs are often directly proportional to each other. Larger dimensions allow larger power sources to be carried, thereby extending flight duration. This increased endurance significantly enhances the operational efficiency of NTARs for reconnaissance, surveillance, and similar missions; however, it also implies that such NTARs have larger physical dimensions. In modern warfare, the concealment of NTARs is of paramount importance because small NTARs are less likely to be detected. Consequently, the trend in the future development of NTARs will involve achieving smaller sizes and longer endurance, with size and endurance continuing to be pivotal factors.

4.2.2. Mechatronic integration

Many existing NTARs have relatively complex mechanical designs involving numerous components and connectors. This complexity increases the challenges associated with manufacturing, maintenance, and repair. Complex mechanical designs are often accompanied by high energy consumption, which poses a challenge for battery-powered NTARs. In addition, intricate designs may introduce potential points of failure, further compromising the reliability of NTARs. Mechatronic integration technology seamlessly combines the electrical components and mechanical structures of NTARs, thereby reducing the complexity of mechanical structures and decreasing the weight and volume of aerial robots [147]. This integration enables closer collaboration between mechanical and electrical systems and enhances precise control over the system. Mechatronic integration can also incorporate various sensing technologies, including vision, sound, laser, and radar sensors, thereby providing a more comprehensive environmental awareness. Consequently, mechatronic integration plays a pivotal role in advancing the performance, expanding the applications, and facilitating broader commercial and scientific uses of NTARs.

4.2.3. Complex scenarios

As the key technologies of NTARs progressively mature, the future applications of NTARs will become more challenging. For example, controlling NTARs through extremely narrow passages tests their path planning and control capabilities. In environments with multiple obstacles, precise environmental perception is vital for avoiding collisions between NTARs and obstacles, even when Global Positioning System signals are unavailable. Under extremely high- or low-temperature conditions, communication may experience interference or constraints. Therefore, the development of robust communication technologies is essential to ensure reliable communication between NTARs and ground control stations (GCSs) or other NTARs. To ensure the stable operation of NTARs in diverse scenarios, future efforts should focus on enhancing the control, perception, and communication technologies for NTARs.

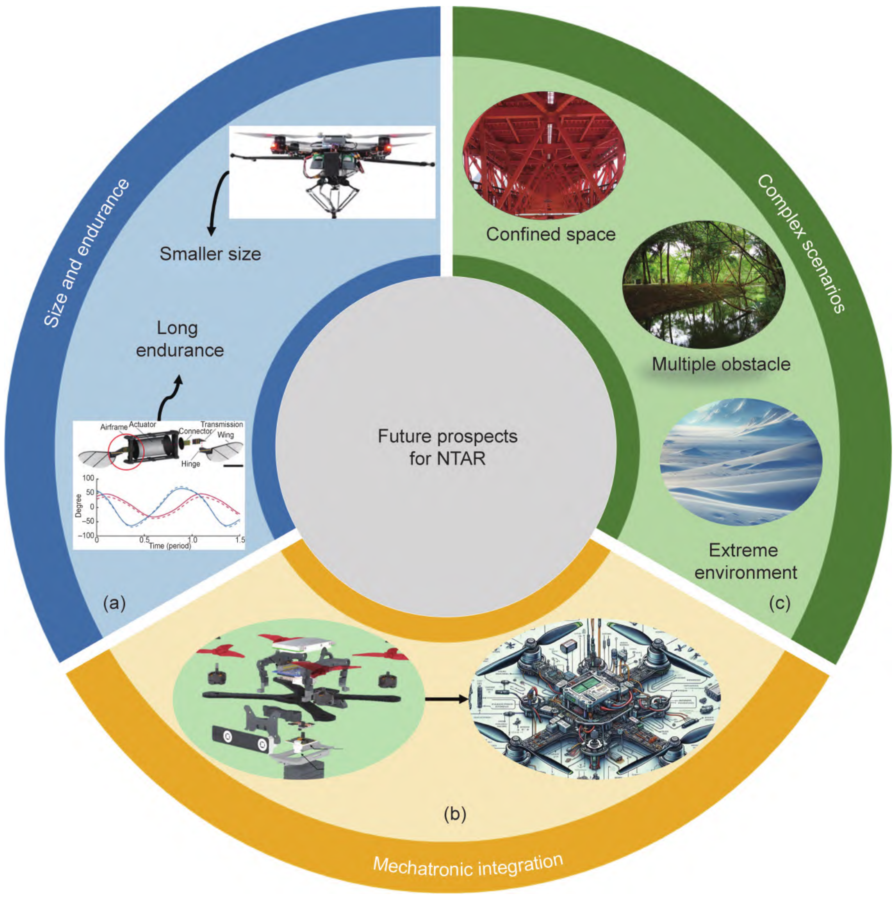

Fig. 7. Three main trends in the future development of NTARs. (a) Size and endurance; (b) mechatronic integration; (c) complex scenarios. (a) Reproduced from Refs. [26,137] with permission; (b) reproduced from Ref. [29] with permission.

5. Conclusions

This paper began by defining NTARs and characterizing them as aerial robots possessing four key features: morphability, biomimicry, multi-modal locomotion, and manipulator attachment capabilities. Subsequently, a comprehensive overview of NTARs was presented. Three pivotal aspects of NTARs—namely, materials and manufacturing technologies, actuation techniques, and perception and control technologies—were presented, and recent research advancements were analyzed and discussed. This study categorized and summarized four types of novel aerial robot systems: FWMAVs, perching aerial robots, amphibious robots, and operational aerial robots. This summary highlighted the most recent cutting-edge research achievements. Finally, a preliminary exploration of the challenges currently presented by NTARs and future development trends was conducted, thereby providing a reference for further research directions.

Acknowledgments

This work was supported in part by the National Key Research and Development Program of China (2022YFB4701800 and 2021ZD0114503), the National Natural Science Foundation of China (62103140, U22A2057, 62173132, and 62133005), the Hunan Leading Talent of Technological Innovation (2022RC3063), the Top Ten Technical Research Projects of Hunan Province (2024GK1010), the Key Research and Development Program of Hunan Province (2023GK2068), and the Science and Technology Innovation Program of Hunan Province (2023RC1049).

Compliance with ethics guidelines

Xidong Zhou, Hang Zhong, Hui Zhang, Wei He, Hean Hua, and Yaonan Wang declare that they have no conflict of interest or financial conflicts to disclose.

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